QUALITY CONTROL OF THE AIR-VOID SYSTEM IN HARDENED CONCRETE

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SYNOPSIS

Experiences from extensive testing of air-void characteristics in hardened concrete specimens, mainly from offshore concrete platforms built in Norway over recent years but also from a number of other structures are reported. The majority of specimens had a relatively low air-void content, and only about half of the specimens had appropriate air-void characteristics. Although higher total air contents generally improved both specific surface and spacing factor, a high air content did not necessarily provide appropriate air-void characteristics. Very good characteristics were also observed for total air-void contents as low as 2,6 to 3,0 percent. The paste content in the specimens often showed considerable deviation from the paste content calculated on the basis of mix proportions. This deviation was substantially larger for specimens separately cast than for cores drilled out from existing structures.

Keywords: Air-entrainment, air-void system, frost resistance, quality control

INTRODUCTION

For many years the relevancy of conventional freeze-thaw testing of hardened concrete has been questioned [1,2], and conventional freeze-thaw testing may also be quite time consuming. In order to obtain a relatively quick assessment of the potential frost resistance, extensive testing of air-void characteristics in hardened over recent years at the Norwegian Institute of Technology, NTH. Most of these measurements have been part of more comprehensive quality control programs carried out on contract basis for the construction industry mainly in Norway, but also in other countries.

A great part of the testing has been related to the extensive construction programs for offshore concrete platforms for oil and gas explorations in the North Sea starting with the Ekofisk tank in 1972 [3]. Since that time a number of platforms have been placed in the North Sea. In addition to quality control of concrete from these platforms testing has also been carried out for a number of other types of concrete structures, such as bridges, dams and harbor structures, for all of which adequate frost resistance and strict quality control have been required. Some of the testing has also been carried out for manufacturers of air-entraining admixtures.

For many of the structures it has been a problem to meet the combined requirements of high compressive strength, e.g. 50 or 60 MPa, and high air content in the concrete (4-6 percent) based on local aggregates available. For these structures it has been crucial to keep the total air-void content in the concrete not higher than strictly neccessary in order to provide adequate frost resistance. It is primarily the amount of smaller air voids, i.e. below 300 μm, which is related to the frost resistance [4]. Since the larger voids only reduce the general level of concrete quality, efforts should be made to keep the amount of these voids at a minimum.

In the following some of the experiences from the testing of air-void characteristics in hardened concrete are reported. It should be noted, however, that for a more complete assessment of adequate frost resistance, also other factors should be considered in addition to the air-void characteristics. That is primarily the permeability of the concrete and the conditions of exposure.

2 TESTING PROCEDURE AND EQUIPMENT

2.1 Concrete specimens

Test results from altogether 80 different concretes are reported, the mix design of which varied within a wide range as shown in Fig 1. Most of the specimens, however, were of high quality concrete with the water-cement ratio and the cement content varying from 0,35 to 0,45 and 400 to 500 kg per m^3 of concrete, respectively. The volume fraction of cement paste calculated on the basis of mix design data varied from 24 to 40 percent. The maximum aggregate size varied from 16 to 32 mm, but was mostly within the range of 20 to 25 mm.

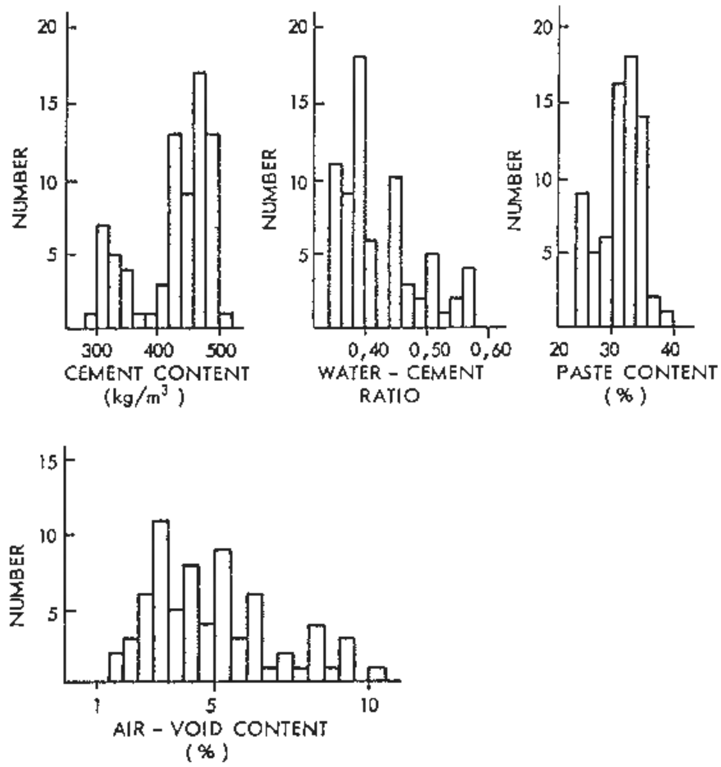


Fig 1. Data on fresh concrete for the specimens tested.

In addition to air-entraining admixtures also combinations with water-reducing and set-retarding agents had frequently been used. Mostly, the combined water-reducing and set-retarding agents were sodium lignosulfonate containing small amounts of vinsol resin type. The air content in the fresh concrete varied from about 1,5 to 10,5 percent (Fig 1). It should be noted that for one concrete an expanding type of admixture had been used (10,5 percent), and six of the concretes had not been added any air entrainment agent at all (2,0 - 3,1 percent).

Most of the specimens tested were 100 mm and 150 mm cubes. The rest of the spesimens were mainly 100 mm cores drilled out from existing structures and a few irregular pieces of concrete removed from precast elements.

2.2 Preparation

Only with a few modifications the cutting and preparation procedures for the specimens were essentially as described in ASTM C 457 (5). Depending on the maximum aggregate size the total section area to be examined microscopically varied from 8.000 to 15.000 mm^2. In order to obtain a statistically representative section for examination the specimens were normally cut as demonstrated in Fig 2, the section being parallell to the top surface of the specimens.

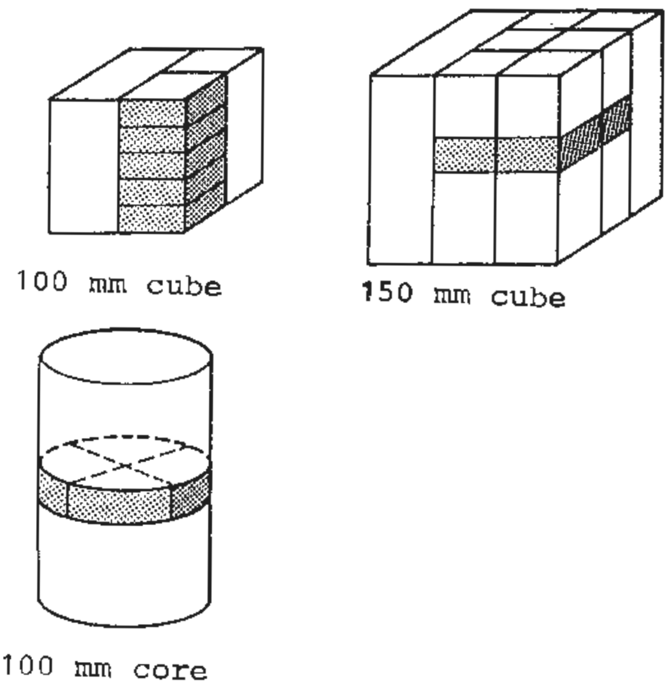


Fig 2. Cutting of specimens.

2.3 Equipment

Two different sets of equipment were employed, one for modified point-count measurements and the other for linear traverse measurements, both types essentially as described in (5), though with automatic operation. Direct microscopic observation at magnification and light conditions as described in (5) were used.

2.4 Measurements and calculation

For all concrete specimens the measurement and calculation of the air-void system were carried out according to the procedure designated as "Based on air-paste ratio" in (5). Thus, the paste fraction of the specimens was also measured in addition to the air voids. The air void content (A_c) was calculated on the basis of the observed fractions of air voids (A_f) and paste (p) as well as the paste fraction (p^1) obtained from the mix design, according to ASTM (5), only modified with a more clear notation:

$$A_c = \frac{100 \cdot A_f/p}{A_p/p + 100 \cdot p^1} \qquad (1)$$

The direct observation of the paste content and the corrected calculation of the air-void content (A_c) made a comparison with the observed fraction of the air-void content (A_f) possible. The measured paste content also made it possible to control the paste-aggregate ratio in the specimens.

For a number of the specimens the void-size distribution was also determined by registration of chord length distribution and a calculation procedure described by Lord and Willis (6).

3 TEST RESULTS AND DISCUSSION

3.1 Air-void characteristics

An overall view of the observed air-void contents, specific surfaces, and spacing factors is shown in Fig 3. Apart from two specimens the rest of the specimens had air-void contents varying from 1,0 to 7,5 percent, 90 and 53 percent of which had air-void contents below 6 and 4 percent, respectively. Recommended air-void contents are always related to the maximum aggregate size. Since the maximum aggregate size was mostly within 20 to 25 mm the majority of specimens had a relatively low air-void content compared with normal requirements. The specific surface and the spacing factor varied from 7 to 60 mm^2/mm^3 and from 0,07 to 1,4 mm, respectively. Of all the specimens 50 percent had a specific surface above 25 mm^2/mm^3 and 58 percent had a spacing factor below 0,24 mm. Since the specific surface and the spacing factor should preferably be above 25 mm^2/mm^3 and below 0,25 mm, respectively, in order to provide good frost resistance (7-8), only about half of the specimens had appropriate air-void characteristics.

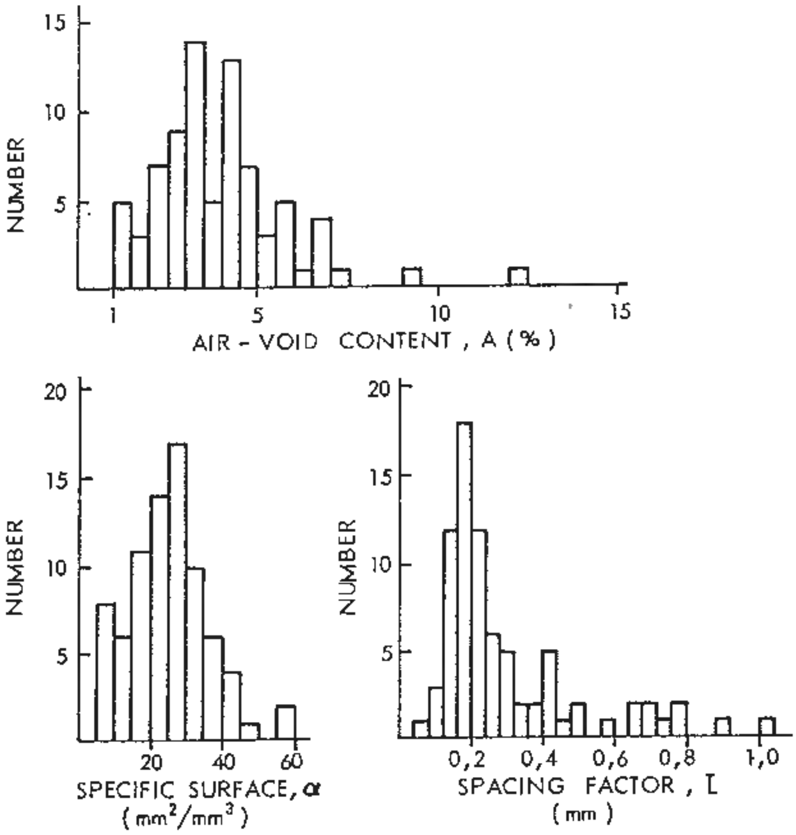


Fig 3. Air-void characteristics of specimens tested.

It should be noted, however, that a high air-void content in the concrete does not necessarily mean appropriate air-void characteristics. This is clarely demonstrated in Figs 4 og 5 where the air-void content is related to the specific surface and the spacing factor, respectively. From Fig 4 it can be seen that the specific surface was both higher and lower than 25 mm^2/mm^3 for air-void contents in the whole range from about 2 to 7 percent. Correspondingly, Fig 5 shows spacing factors both lower and higher than 0,25 mm for air-void contents in the whole range from about 2,5 to 6 percent. Five of the specimens with low air volumes in the range of 2,6 to 3,0 percent had very good air-void characteristics with a specific surface of 35 to 40 mm^2/mm^3 and a spacing factor 0,17 to 0,20 mm. Six of the specimens with intermediate air volumes in the range of 3,0 to 3,6 percent had a specific surface of only 12 to 17 mm^2/mm^3 and a spacing factor as high as 0,40 to 0,50 mm. Even for higher air volumes in the range of 4,0 to 6,0 percent did six of the specimens have a specific surface of not more than 18 to 22 mm^2/mm^3, while the spacing factor varied from 0,23 to 0,31 mm. Thus, although Figs. 4 and 5 demonstrate that higher total air volumes generally tend to improve both specific surface and spacing factor, the results also demonstrate that a high air volume does not necessarily provide appropriate air-void charateristics. Very good characteristics can also be obtained for quite low air volumes. There are a number of factors affecting the air-void system in concrete of which appropriate admixtures, mix design and mixing procedure are essential. In addition to measurement of the total air volume in the fresh concrete Figs. 4 and 5 clearly demonstrate that control of the air-void characteristics in the hardened concrete should also be an important part of the quality control. For lower air volumes such a control should be specially important.

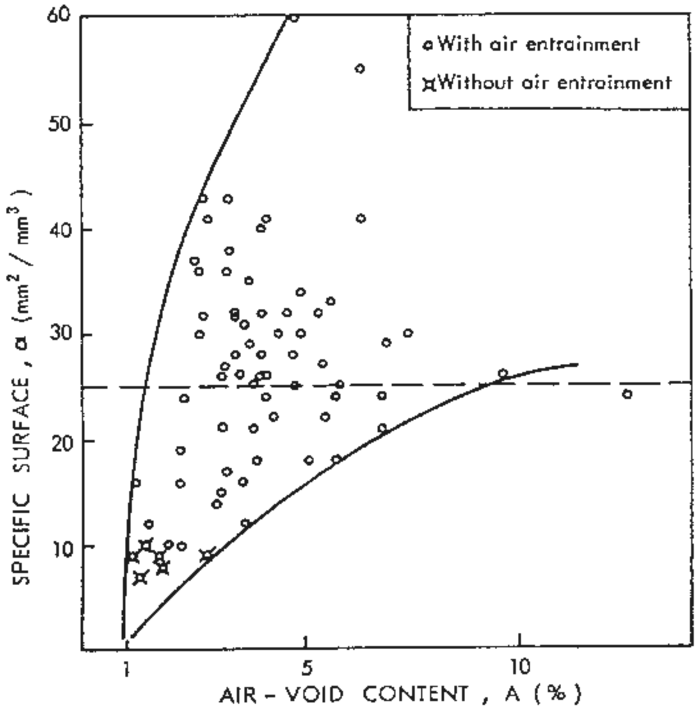


Fig 4. Specific surface versus air-void content.

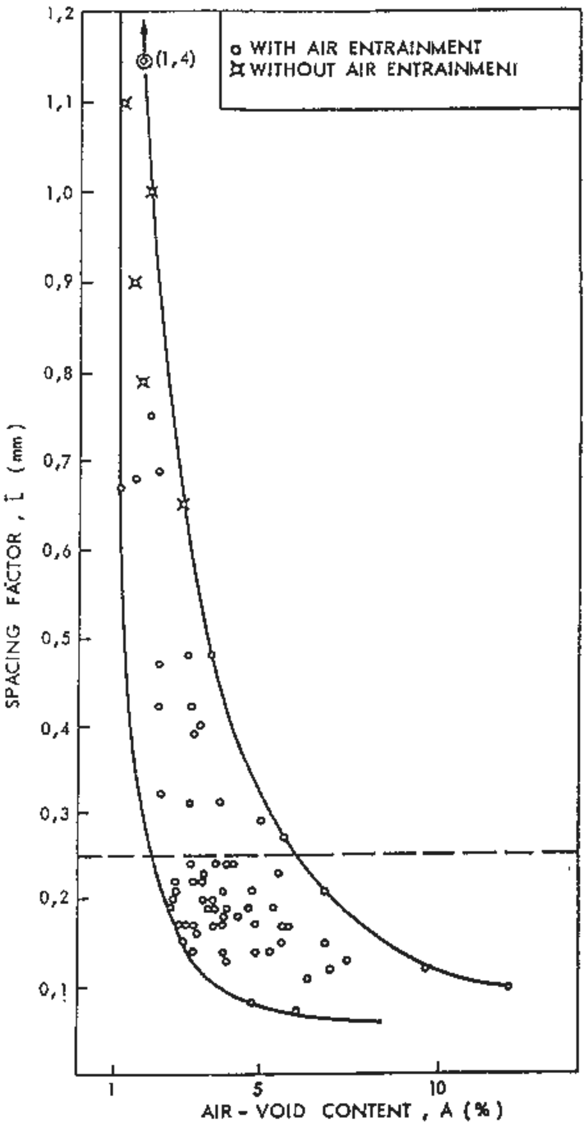
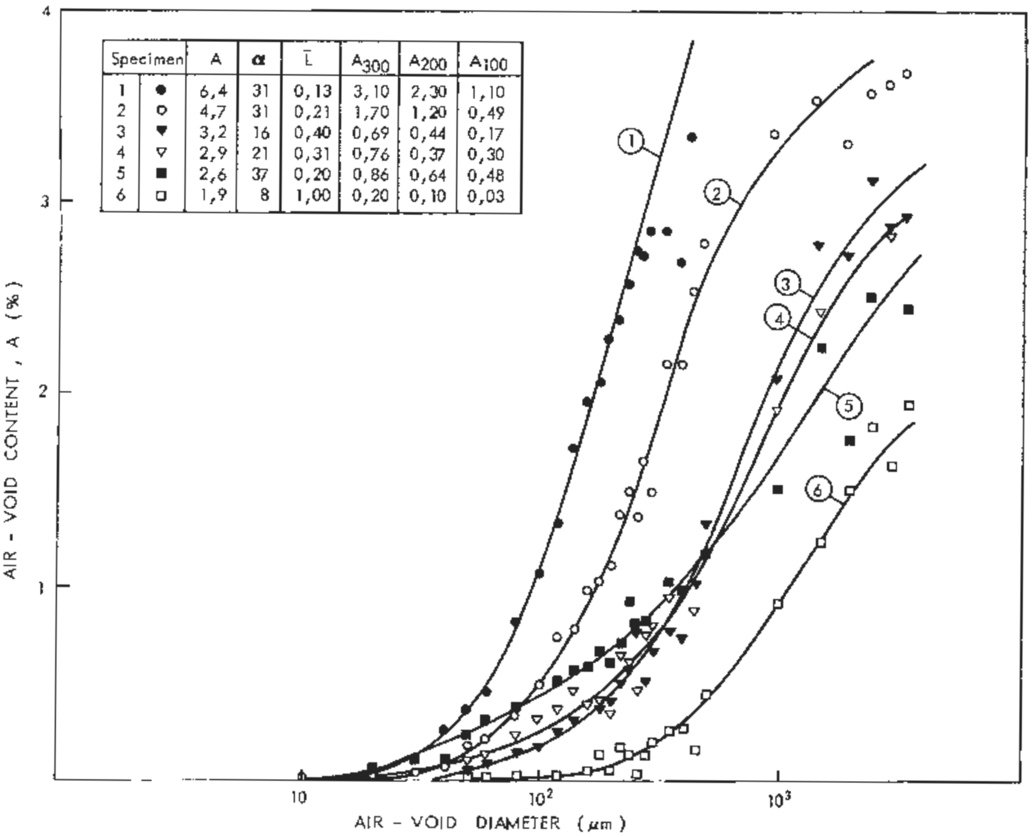


Fig 5. Spacing factor versus air-void content.

3.2 Void-size distribution

In order to see how the air-void characteristics are related to the void-size distribution in the concrete a number of measurements were carried out, some typical results of which are shown in Fig 6.

As can be seen from Fig 6 specimen 1 had a void-size distribution indicating a very high content of both smaller and large air-voids. Since the specific surface (α) was high (31 mm^2/mm^3) and the spacing factor (L) was very low (0,13 mm), both of these characteristics appear very good. A total air volume (A) of 6,4 percent is also very high, however.



Specimen		A	α	$\bar{L}$	A_{300}	A_{200}	A_{100}
1	●	6,4	31	0,13	3,10	2,30	1,10
2	○	4,7	31	0,21	1,70	1,20	0,49
3	▼	3,2	16	0,40	0,69	0,44	0,17
4	▽	2,9	21	0,31	0,76	0,37	0,30
5	■	2,6	37	0,20	0,86	0,64	0,48
6	□	1,9	8	1,00	0,20	0,10	0,03

Fig 6. Typical void-size distributions.

Specimen 2 had an air volume (A) of 4,7 percent which was lower than in specimen 1. Although (α) was the same (31 mm^2/mm^3) the lower content of smaller air voids in Fig 6 is reflected by a substantially higher (L) of 0,21 mm.

For specimen 3 the total air volume (A) was even lower (3,2 percent), but also (α) was very low (16 mm^2/mm^3) and (L) was very high (0,40 mm). The diagram in Fig 6 indicates a low content of smaller voids and a relatively high content of larger voids, demonstrating that this particular air entrainment was not very successful.

Specimen 4 had a total air volume of 2,9 percent. Although both (α) (21 mm^2/mm^3) and (L) (0,31 mm) as well as the whole void-size distribution appear somewhat better than for specimen 3, this entrainment was not very successful either.

Specimen 5 had only a total air volume of 2,6 percent, while (α) was very high (37 mm^2/mm^3) and L was relatively low (0,20 mm). These good air-void characteristics correspond very well with the highly appropriate void-size distribution shown in Fig 6, demonstrating a successful air entrainment.

Specimen 6 was taken from a concrete without any air entrainment. The total air volume was 1,9 percent, while (α) and (L) were 8 mm²/mm³ and 1,0 mm, respectively. These poor air-void characteristics are closely corresponding to the unappropriate void-size distribution demonstrated in Fig 6.

In order to obtain a good assessment of the void-size distribution in the concrete, the results shown in Fig 6 demonstrate that several air-void characteristics should be considered together. Most frequently the air-void system is described by use of (A), (α) and (L). It should be noted, however, that the specific surface (α) is strongly dependent on the air-void content (A) and hence not so suited as a characteristic of the air-void system.

According to Schäfer(4) it is primarily the space capacity of the air-voids with diameters below 300 μm (A_{300}) which is the determining factor for the frost resistance. In addition to A_{300} the corresponding values for diameters below 200 and 100 μm are also shown in Fig 6. These caracteristics reflect very well the difference in void-size distribution for the important lower parts of the diagrams. Therefore, in addition to (A), (α) and (L), (A_{300}), (A_{200}) and (A_{100}) were also used as characteristics for assessment of the air-void system.

3.3 Air-void content in fresh versus hardened concrete

By comparing Figs. 1 and 3 it can be seen that the air-void content in hardened concrete was generally lower than in fresh concrete. In order to obtain a better basis for comparison all data on air-void contents are plotted in Fig 7, including both corrected (A_c) and uncorrected (A_f) air-void contents for the hardened concrete. From Fig 7 it can be seen that the majority of data fall below the line of equality, demonstrating the generally higher air contents in the fresh concrete. These findings are in accordance with experiences previously reported (9). For the hardened concrete it can also be seen that the corrected values (A_c) were generally higher than the uncorrected values (A_f).

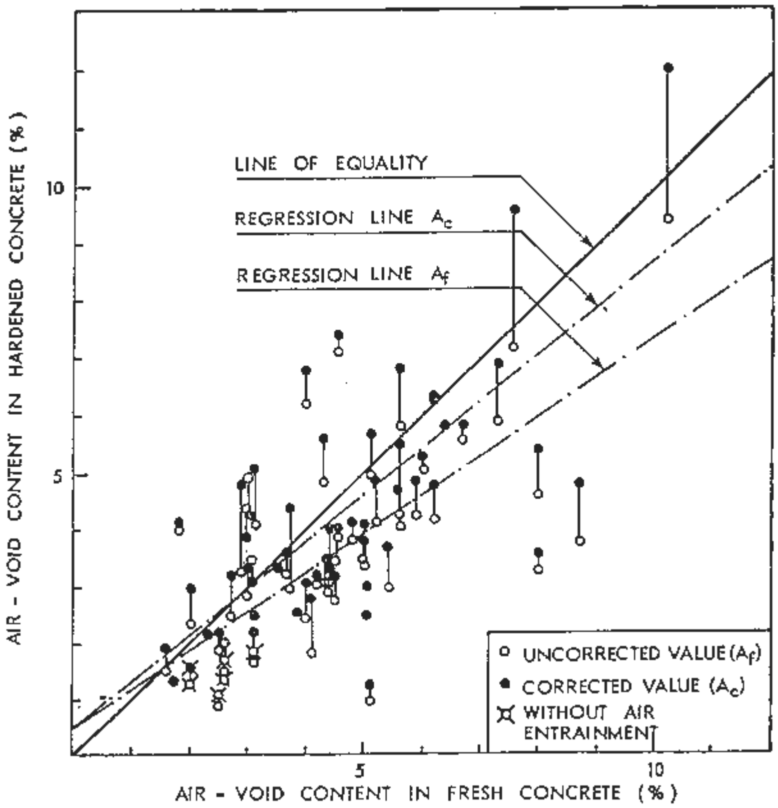


Fig 7. Air-void content in fresh versus hardened concrete.

For further comparison of the air-void content in fresh and hardened concrete regression analysis for three groups of specimens were carried out, the results of which are shown in Table 1. Group 1 includes all specimens for which data on the air-void content in fresh concrete were available, while groups 2 and 3 only include 100 mm and 150 mm cubes, respectively. From Table 1 it can be seen that no distinct difference in correlation for the two different cube sizes was observed. For all three groups, however, the correlation was generally better for the corrected values of air-void contents (A_c) than for the uncorrected values (A_f). This can also be seen in Fig 7 where the regression lines are plotted for group 1.

Table 1. Air-void content in fresh versus hardened concrete expressed by regression coefficients for y = ax+b and coefficient of correlation (r^2).

Group of specimens		1	2	3
Number of specimens		61	24	21
A_c	a	0,82	0,71	0,70
	b	0,50	1,1	1,2
	r^2	0,45	0,38	0,45
A_f	a	0,68	0,59	0,51
	b	0,53	0,95	1,7
	r^2	0,44	0,39	0,35

Group 1: All specimens for which data on air-void content in fresh concrete was available

Group 2: 100 mm cubes only

Group 3: 150 mm cubes only

3.4 Paste content

At an early stage of air-void measurements it was observed that the paste content (p) in some of the specimens showed considerable deviation from the paste content calculated on the basis of mix proportions (p^1). Consequently, measurements of (p) was introduced as part of the routine control, thereby providing a basis for both determining corrected air-void content (A_c) and checking the paste-aggregate ratio.

Of the different types of specimen the deviation in paste content between observed values (p) and calculated values (p^1) was substantially larger for separately cast specimens than for cores drilled out from existing structures. For 25 specimens of the 100 mm cubes the p/p^1 ratio varied from 0,57 to 0,96 with an average of 0,79, and for 21 specimens of the 150 mm cubes the ratio varied from 0,70 to 0,94 with an average of 0,85. For 12 specimens of the 100 mm cores the ratio varied from 0,82 to 1,08 with an average of 0,99. These results indicate that specimens separately cast may not be as representative for the bulk of concrete as cores drilled out from a larger volume of the concrete. Of separately cast specimens the 150 mm cubes may also be more representative than the 100 mm cubes. The generally low p/p^1 ratio observed also explains why the corrected air-void content (A_c) was generally higher than the observed fraction of air-voids (A_f).

As previously described for cutting of the specimens the total section to be examined consisted of 4 to 6 smaller sections removed from different parts of the specimen (Fig 2). For the 100 mm cubes these smaller sections were normally removed from different levels below the top surface, while for the 150 mm cubes and the 100 mm cores the sections were normally removed only from one level. Individual determinations of the paste content for each of these smaller sections provided a certain basis for also checking the homogenity of the concrete specimens.

Although data from different sections within one level and different levels in the specimens are not directly comparable, the individual variation of paste content was substantially larger in the 100 mm cubes compared with the 100 mm cores, some typical results are shown in Fig 8. In this figure data from five sections in five different levels in a cube and four sections within one level in a core are shown. Frequently, the paste content was more inhomogeneously distributed in the separately cast cubes, while more homogeneously distributed in the drilled out cores. For the cubes the paste content was generally lower in the bottom part of the specimens. Information from several construction sites indicates that for most of the cubes the concrete had been compacted by vibration and a possible overvibration may explain the segregation observed.

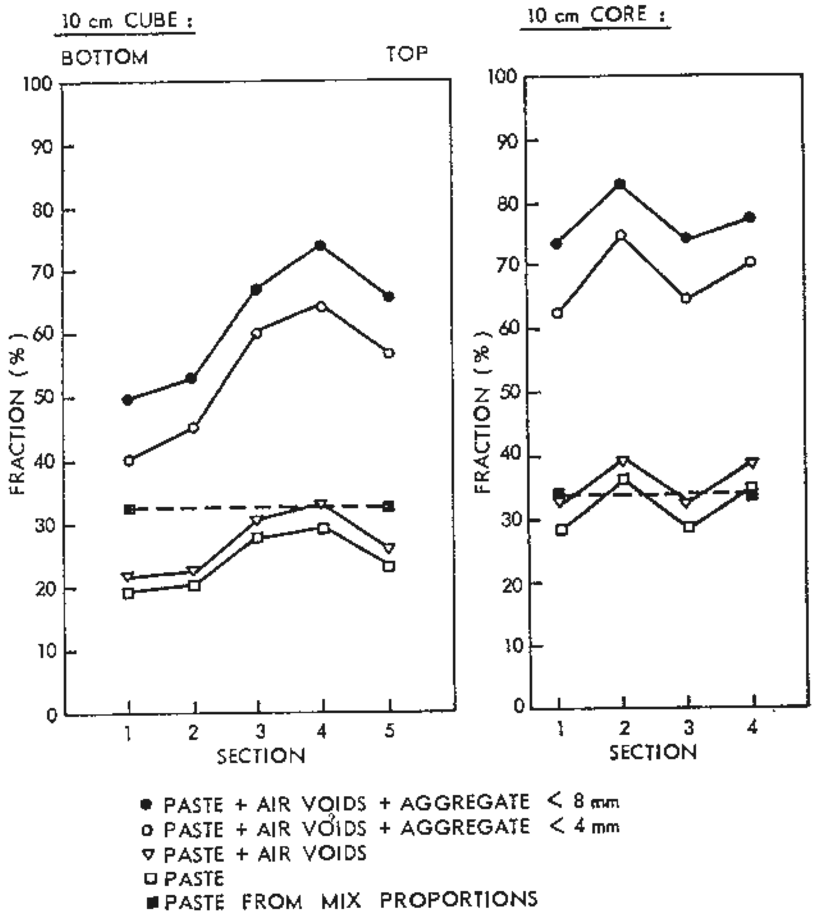


Fig 8. Typical variations in paste content.

In Fig 8 information about the content of coarser aggregate is also indicated [1]. Since the measurements of coarser aggregate contents are based on cut sections of aggregate above 4 and 8 mm, it should be noted that these data represent contents of aggregate somewhat coarser than 4 and 8 mm, respectively. From Fig 8 it can be seen, however, that the variation in content of coarser aggregate appears to be a most important factor for an understanding of the observed variation in paste content.

4 CONCLUSIONS

The test results reported in the present paper are based on an extensive quality control of concrete from a varyity of different construction sites and existing concrete structures. Based on this quality control the following experiences can be summarized:

(1) Of all test specimens 90 and 53 percent had air-void contents below 6 and 4 percent, respectively. Since the maximum aggregate size was mostly within 20 to 25 mm, the majority of specimens had a relatively low air-void content.

(2) Of all test specimens 50 percent had a specific surface above 25 mm^2/mm^3 and 58 percent had a spacing factor below 0,24 mm. Since the specific surface and the spacing factor should preferably be above and below these limits, respectively, only about half of the specimens had appropriate air-void characteristics.

(3) Although higher total air volumes generally improved both specific surface and spacing factor, a high air volume did not necessarily provide appropriate air-void characteristics. Very good characteristics were also observed for quite low air volumes (Figs. 4 and 5). Five of the specimens with low air volumes in the range of 2,6 to 3,0 percent had a specific surface of 35 to 40 mm^2/mm^3 and a spacing factor 0,17 to 0,20 mm, while six of the specimens with high air volumes in the range of 4,0 to 6,0 percent had a specific surface of only 12 to 17 mm^2/mm^3 and a spacing factor as high as 0,40 to 0,50 mm. Therefore, observation of the air-void characteristics in hardened concrete should be an important part of the quality control where high frost resistance is required.

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1) Based on separate point count at low magnification

(4) A total evaluation of all the three air-void characteristics (A), (α), and (L), should provide a good overall basis for assessing the void-size distribution in concrete (Fig 6). However, additional information about (A_{300}), (A_{200}) and (A_{100}) gives a more complete assessment of the air-void system in the concrete.

(5) The air-void content in hardened concrete was generally lower than in fresh concrete (Fig 7). In the hardened concrete the corrected air-void contents (A_c) were generally higher than the uncorrected values (A_f), for which the paste content only had been calculated on the basis of mix proportions.

(6) The paste content observed in the specimens (p) often showed considerable deviation from the paste content calculated on the basis of mix proportions (p^1). Of the different types of specimen this deviation was substantially larger for specimens separately cast than for cores drilled out from existing structures. For 25 specimens of the 100 mm cubes the p/p^1 ratio varied from 0,57 to 0,96 with an average of 0,79, while for 12 specimens of the 100 mm cores the ratio varied from 0,82 to 1,08 with an average of 0,99. Thus, separately cast specimens may not be as representative for the bulk of concrete as cores drilled out from existing structures.

(7) 100 mm cubes showed a larger variation of the paste-aggregate ratio within the same specimen compared with 100 mm cores drilled out from existing structures. This appears to be due to poor preparation of specimens giving a variable content of coarse aggregate.

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